M.R.P. 929
S.C. 111/189
10th SEPTEMBER, 1955

The energy balance of surface and atmosphere at Kew, May 1953 to April 1954

by

G.D. Robinson

(Meteorological Office)

METEOROLOGICAL
OFFICE
- 8 FEB 1956
LERWICK OBSERVATORY
SHETLAND

AIR MINISTRY

METEOROLOGICAL RESEARCH COMMITTEE

At the time of issue this report has not been published. Any author desiring to quote this paper should refer to it as "A paper of the Meteorological Research Committee (London), M.R.P. No. 929 by Dr. G.D. Robinson. A copy is available in the Library of the Meteorological Office."

M.R.P. 929
S.C.III/189
10th September, 1955

AIR MINISTRY
METEOROLOGICAL RESEARCH COMMITTEE

The energy balance of surface and atmosphere at Kew, May 1953 to April 1954

by

G.D. Robinson (Meteorological Office)

SUMMARY

An estimate is made, based mainly on surface measurements, of the net radiation entering or leaving the system atmosphere plus surface layer of earth at Kew during the whole period May 1953 - April 1954, inclusive, and for separate periods of three summer and three winter months. The heat liberated by phase changes of H_2O and the heat conduction from the system to the ground are also estimated. The deduced dynamical and advective heating is compared with the latitude means derived from similar world wide studies, and from published studies of the meridional eddy flux of heat.

In the course of this work new estimates are made of the local albedo of the planet for visual plus ultra-violet, infra-red, and total radiation, and of the photometric albedo.

The bearing of the results on methods of implementing the programme of radiation measurements during the International Geophysical Year 1957-58 is examined.

1. INTRODUCTION

In the programme of meteorological observations planned for the International Geophysical Year 1957-58 it is recommended that certain radiation measurements be made at cooperating stations, as part of a large scale investigation of atmospheric circulation. Ideally measurements are needed of the net flux of radiation over a surface representative of a wide area of the surroundings of the station, and at all heights in the atmosphere. There are at present no techniques for measuring radiation from balloons, and should one be developed it can hardly be used on more than an experimental scale. Measurements of solar radiation from aircraft are possible and methods for measuring terrestrial radiation from aircraft have been tried out, but expense forbids any general use of these. The most that can be expected from all but a few I.G.Y. stations is a record of the flux of total radiation at the ground and perhaps a separate record of solar radiation. Such measurements have been made for a trial period of one year at Kew Observatory (Roach 1955, Blackwell 1954b), and the purpose of the present paper is to show how they can be used to further the I.G.Y. investigation.

The problem is to determine the flux of radiation at any level in the atmosphere from surface measurements; it falls into two parts concerned respectively with solar and terrestrial radiation. No new suggestions will be offered here concerning the latter, and attention will be restricted to the whole depth of the atmosphere, reducing the problem to a determination of the local value of the albedo of the earth and atmosphere at different seasons of the year.

/2.

2. THE ALBEDO OF THE ATMOSPHERE

Direct measurement of the earth's albedo requires observation from outside the atmosphere. The nearest approach to this ideal is the method of Danjon involving photometry of the earthlit part of the moon. Danjon's observations were visual, and give the albedo of the planet at different wavelengths in the visual range. Fritz (1949) has applied Danjon's measurements to an estimate of the albedo of the planet for the whole solar radiation (" total albedo "). To do this he was obliged to consider the absorption of the solar infra-red radiation, and in particular to assume values for the absorption in cloud. H.G. Houghton (1954) has estimated the albedo of the planet from measurements of solar radiation at the ground and assumed atmospheric absorptions. Drummond and van Deventer (1954) have derived a local albedo, that of the South African plateau and its atmosphere, in the same way. The method here applied to the Kew observations is essentially that of Drummond and van Deventer, with the advantage that the continuous record of illumination at the ground allows a separate estimate of the photometric albedo and the splitting of the total albedo into the contribution from the infra-red and visual plus ultra-violet ranges.

It was shown by Blackwell, Eldridge and Robinson (1954) that in cloudless conditions the Kew illumination and radiation records are self-consistent if there is present in the atmosphere a grey absorber, in addition to the known gaseous absorbers, which removes about 10% of the incident radiation, and if at the same time the illumination measurements are about 5% too high. Blackwell (1954a) estimated an accuracy of about ±5% for the long term means of illumination, and there is independent evidence, discussed by Blackwell, Eldridge and Robinson, that the Kew measurements are high. However it has been pointed out to me by Mr. D.B. Lake that the records are also self-consistent if the illumination measurements are correct, grey absorption in the atmosphere is small, and backward scattering from the haze is much greater than previously assumed, as a result of multiple scattering. It is hoped that aircraft observations will resolve this doubt in the near future. In this paper both possibilities are examined. That involving absorption by haze of about 10%, which is considered the more probable, will be called case a; that involving high backward scattering from haze case b.

Making the reasonable assumption that absorption of visible light by cloud droplets is negligible the photometric albedo can be determined directly, since only ozone absorption and haze absorption are concerned, and the extraterrestrial illumination is known. (Appendix 1). The total albedo follows in the same way from the total radiation at the ground, with the additional difficulty of allowing for absorption in cloud. There is very little information on which to base this estimate; the possibilities have been discussed by H.G. Houghton (1954). Practically all cloud absorption must be in the infra-red region, so that it is advantageous to consider separately the albedo in the infra-red and visual + ultra-violet ranges.

Blackwell (1954a,b) has shown that the mean value of the luminous efficiency of daylight, i.e. the mean ratio of illumination to total radiation, is practically the same in cloudless, mean, and overcast conditions at Kew. No large errors will be introduced by extrapolating this result and saying that the ratio of energy at the ground in the ultra-violet + visual range to that in the infra-red range is the same in the mean as in cloudless conditions. No direct measurements of either range are available at Kew, but measurements of solar intensity in the range $\lambda < 0.64\,\mu$ have been made and discussed by Blackwell, Eldridge and Robinson. Table VII of their paper allows an estimate of the ratio visible + ultra-violet energy to infra-red energy on a number of cloudless occasions. It turns out to be 0.9 ± 0.1 if the division is made at $\lambda = 0.70\,\mu$. Applying this to the measurements of

/total

total radiation at the ground gives separate estimates of the two ranges. The incoming energy in the two ranges at the limit of the atmosphere is known (Appendix I). If probable and limiting assumptions concerning the various absorptions are now made probable and limiting values of the various albedos follow.

Computations were based on the records for the period May 1953 to April 1954, to allow combination with Roach's results for the heat balance at the ground over this period. It can however be seen from Table I that the solar radiation measurements for this year did not differ appreciably from the mean of the five year period 1947-51 treated by Blackwell. In addition to the whole year, summer conditions - May, June and July -, and winter conditions - November, December and January -, were considered. In view of the expected degree of accuracy it was not thought appropriate to treat the observations hour by hour and integrate over all solar altitudes, so a weighted mean solar altitude $\bar{h}$ ($\sin \bar{h} = \int A \sin h \, dt / \int A \, dt$, where A is the observed radiation or illumination on a horizontal surface at solar altitude h and the integrals are from sunrise to sunset over the period concerned), was derived. The absorptions by O_3 and H_2O in a model cloudless atmosphere containing 2 cm. H_2O and 2 mm. O_3 had been used by Blackwell, Eldridge and Robinson; values appropriate to the present problem are shown in Table II, together with the additional absorption attributed to haze.

Computation of the albedo now proceeds in the following manner. For the photometric albedo the observed illumination at the ground is first corrected to remove that part contributed by reflection from the atmosphere of radiation reflected at the ground. It is necessary to assume albedos for ground and atmosphere to arrive at this correction; 0.1 and 0.6 were used. The corrected illumination, here designated that "reaching the ground direct", is subtracted from the extraterrestrial illumination and expressed as a fraction of the latter. In the tables this fraction appears as "albedo + absorption". Subtraction of an assumed absorption leaves the albedo. A similar procedure is followed for the visual + ultra-violet and infra-red ranges, the observed radiation at the ground being split between the ranges in the manner indicated above. For the re-radiation correction the albedos assumed in the visual + ultra-violet range were the same as for the illumination; in the infra-red range 0.2 was used as surface albedo and 0.4 for the atmosphere. One example will now be given in detail.

Period May 1953 - April 1954 inclusive.

1. Determination of photometric albedo

Extraterrestrial illumination (mean)	29.0 kilolux (kl.)
Illumination recorded at ground	13.8 kl.
Correction for re-reflection	0.7 kl.
Illumination reaching ground direct	13.1 kl.

Albedo + Absorption 0.55 (case b)
If illumination record is 5% too high
Albedo + Absorption 0.58 (case a)

Case a.
1. If absorption is 7% photometric albedo is 0.51
2. If absorption is 12% photometric albedo is 0.46

Case b.
Absorption is 2.5%, photometric albedo is 0.52^5

2. Determination of albedo in visual + ultra-violet range

Extraterrestrial mean radiation	13.6 mw. cm^{-2}
Total radiation recorded at ground	10.4 mw. cm^{-2}
Ratio visual + ultra-violet/infra-red	0.9
Visual + ultra-violet at ground	4.9 mw. cm^{-2}
Re-radiation correction	0.3 mw. cm^{-2}
Visual + ultra-violet radiation reaching ground direct	4.6 mw. cm^{-2}

Albedo + Absorption 0.66

Case a.

1. If absorption is 10% visual + ultra-violet albedo is 0.56
2. If absorption is 15% visual + ultra-violet albedo is 0.51

Case b.

Absorption is 6%, visual + ultra-violet albedo is 0.60

3. Determination of albedo in infra-red range

Extraterrestrial mean radiation 14.3 mw. cm^{-2}
Infra-red radiation at ground 5.5 mw. cm^{-2}
Re-radiation correction 0.5 mw. cm^{-2}
Infra-red radiation reaching ground direct 5.0 mw. cm^{-2}
Albedo + absorption 0.65

Case a.

1. If absorption is 30%, infra-red albedo is 0.35
2. If absorption is 35%, infra-red albedo is 0.30

Case b.

If absorption is 25%, infra-red albedo is 0.40

The same procedure was followed for the periods May, June, July 1953 and Nov., Dec. 1953 Jan. 1954. The results are collected in Table III, which shows the absorptions assumed in the various cases. Values of the total albedo range over about 15% for each period, but the likely limits can be contracted by an examination of probable absorptions. In mean cloud conditions the effects of haze are likely to be less than in the cloudless atmosphere, if only because of greater ventilation of the polluted region; the following estimates allow for this. The estimated cloud absorption is additional to the full absorption for the appropriate amount of water vapour.

Year.

Haze absorption 5% (grey)
Cloud absorption say 5% to 10% of infra-red
Water content between 1 and 2 cm.
Albedos lie between those for case a.1 and case a.2.

Summer.

Haze absorption 5% (grey)
Cloud absorption 5%-10% of infra-red
Water content 2 cm.
Conditions between b.1 and a.2.

Winter.

Haze absorption 5% to 10% (grey)
Cloud absorption 10% to 20% of infra-red
Water content 1 cm.
Conditions between a.1.2 and a.2.2.

The albedos corresponding to these probable conditions are set out in Table IV. They refer to the atmosphere alone. Assuming an albedo of 0.15 for the land surface (this is confirmed by unpublished measurements made extensively over southern England by the Meteorological Research Flight), and allowing for re-reflection by the atmosphere it is found that 0.03 must be added to the albedo of the atmosphere to give the local value of total albedo of earth + atmosphere. The final estimates of this quantity are

Year	0.475
Summer	0.46
Winter	0.525

and it seems likely that the true values for Kew lie within ±0.05 of these. Over southeast England as a whole the effect of haze must be less than at Kew; it seems reasonable to reduce the estimates by about 0.02.

/If

If the mean cloudiness is known the albedo of the cloudy portion of the atmosphere can be obtained from the mean albedo, using the values of Blackwell, Eldridge and Robinson for the albedo of the cloudless atmosphere which are given in Table II. Taking the mean cloudiness as 0.7 the results listed under "Kew mean" in Table V are obtained. Two sources of comparable data are available. Blackwell (1954 a, b) has tabulated the illumination and total radiation at Kew for persistent overcast conditions (i.e. for periods of at least 3 hours without direct sunshine, the end hours of the periods being ignored), and albedos may be determined from these figures in the same way as for mean conditions. This was done for all occasions (more than 100 hours) during the period 1947-51 with solar altitude h in the range $\arcsin 0.5 < h < \arcsin 0.6$, corresponding to $\bar{h}$ for the year, the absorption being assumed to be the same as in the mean condition. The results are shown in Table V; as would be expected they are considerably higher than the corresponding figures for mean cloud. An entirely independent estimate was obtained by slight manipulation of figures quoted by Fritz (1949) in his extension of Danjon's work. The results set out in Table V follow from Fritz's work without further assumption; they are appropriate to his case 1 and a mean cloudiness of 0.54. In view of the doubts as to the true mean cloudiness appropriate to each investigation and the differences in mean solar altitude, the agreement between the Kew mean and the Fritz/Danjon results is remarkable. Another comparison with Fritz's work is available. F.J. Scrase (private communication) has computed the mean albedo for S.E. England, on the basis of Fritz's figures for cloud, atmosphere, and surface, to be 0.47, less than 0.02 higher than the value here suggested. Finally there is H.G. Houghton's (1954) figure for cloud alone of 0.55; the small difference between this and the mean Kew value being due mainly to different assumptions concerning cloud absorption which in Houghton's words are in each study "little more than an educated guess".

3. TERRESTRIAL RADIATION AT THE LIMIT OF THE ATMOSPHERE

Numerous attempts have been made to estimate the radiation of the earth to space. Of the available methods the radiation chart of Elsasser is the best known, and that of Yamamoto probably the least open to objection. All known methods are inadequate at high levels and it is not even possible to estimate the likely degree of error of the results they yield. The only observations at substantial heights are a few very recent ones by J.T. Houghton (1954) made over southern England with the co-operation of the Meteorological Research Flight.

The earliest reasoned survey of the outgoing radiation is that of Simpson (1929) who found a mean annual value of 18.7 mw.cm^{-2} in 50°N. Typical recent estimates are those of Raethjen (1950) using his own radiation chart and H.G. Houghton (1954) with the Elsasser chart. Raethjen's results for the zone 40°-60° are

Summer half-year	21.2 mw. cm^{-2}
Winter half-year	20.6 mw. cm^{-2}
Yearly mean	20.9 mw. cm^{-2}

Houghton gives for 52°N (by interpolation)

Yearly mean	21.3 mw. cm^{-2}.

Increasing cloudiness decreases this figure, and data given by H.G. Houghton suggest that for the mean cloudiness of southern England his yearly mean value would reduce to 21.0 mw. cm^{-2}. H.G. Houghton states specifically that his figure refers to the tropopause, not to the limit of the atmosphere. Simpson, and Raethjen presumably, computed the radiation leaving the earth, though the computations are so uncertain that the difference between the results for this and for the tropopause radiation are hardly significant.

The measurements of J.T. Houghton were made at near-tropopause levels in cloudless or near cloudless conditions. He found for the upward flux a value

/about

about 22 mw. cm^{-2}, and for the downward flux 3 to 4 mw. cm^{-2}. Presence of the mean cloud cover might reduce the former value by 5 to 10 per cent, and have little effect on the latter. J.T. Houghton's measurements therefore suggest a value of about 18 mw. cm^{-2} for the net radiation at the tropopause in mean conditions over southern England. He himself comments "calculations of the mean outgoing radiation will be very dependent on the assumptions made regarding mean cloud amount, and on the emissivity of high level clouds. Since very little is known about the frequency of occurrence of cirrus clouds of different emissivities it is impossible to predict an accurate value for the mean outgoing radiation, and, in fact, Simpson's rough calculation making it about 18 mw. cm^{-2} may not be far wrong".

Two comments seem necessary on J.T. Houghton's work. In the first place the measurements themselves have some disturbing features. The results for the upward flux at 40,000 ft. are rather less, and for the downward flux rather more than was expected. The same remark applies to his low level measurements at about 3000 ft. Here the measured downward flux is greater than that indicated by standard radiation charts, a result contrary to the experience of Robinson (1947, 1950) and Yamamoto and Sasamori (1954) at the surface. However there is no obvious flaw in Houghton's work and his observations must be given more weight than the suspect calculations. The second comment concerns the relation between the tropopause radiation and that at the limit of the atmosphere. Absorption of solar radiation in the stratosphere in this latitude amounts to roughly 2 mw. cm^{-2} in the mean, so that if the stratosphere is locally in overall radiative balance the mean net outward radiation must increase by this amount above the tropopause. How far the stratosphere is from this radiative balance is at present merely a matter for speculation, and the outgoing radiation remains in doubt to this extent.

The most likely value for the radiation to space over southern England will be taken as 20±3 mw. cm^{-2} in the mean over the year, seasonal variation being probably not more than ±1 mw. cm^{-2}.

4. THE RADIATION BUDGET

The energy changes by radiation of the atmosphere and surface layer at Kew follow from Roach's work and the present results. They are shown in Fig. 1. Table VI reproduces the relevant part of Roach's results. There are minor inconsistencies between Fig. 1 and Table VI mainly connected with the surface albedo. This has been taken as 0.15 in the present study, a value appropriate to a wide area of southern England, whereas the figure used by Roach is that measured for the immediate surroundings of the radiometers at Kew, 0.25.

The figures for the net radiation entering the atmosphere are

Year	-5.5 ± 3.5 mw. cm^{-2}
Three summer months	+3.8 ± 3.5 mw. cm^{-2}
Three winter months	-14.3 ± 3.5 mw. cm^{-2}.

Raethjen (1950) and H.G. Houghton (1954), whose studies of the world wide radiation balance have been mentioned, give tables from which may be interpolated the mean for latitude 52° of the net radiation entering the atmosphere. The values are

H.G. Houghton	Year	-5.0 mw. cm^{-2}
Raethjen	Year	-5.5 mw. cm^{-2}
"	Six summer months	+2.5 mw. cm^{-2}
"	Six winter months	-13.0 mw. cm^{-2}.

In comparing the values it should be remembered that the Kew results are for midsummer and midwinter quarters whilst Raethjen's estimates are means for

the half-year. Nevertheless there is a remarkable agreement. There is no obvious reason why a single station should not differ widely from the latitude mean of net radiation received, and it will be interesting to see whether other stations show the same agreement as Kew.

5. THE ENERGY BALANCE

The heat required to balance that radiated to or from the system can be supplied in a number of ways - by temperature changes of the system, by phase changes of water within the system, by conduction between the system and the deeper layers of the ground, by advection from surrounding air, and by conversion to and from gravitational potential energy in vertical currents within the system, (dynamical heating or "transport of potential energy").

The first three methods can be accounted for by direct measurement. On the assumption that systematic change in the liquid water and ice content of air passing through the system is negligible the amount of water vapour condensed in a period is equal to the measured precipitation. Evaporation at the ground has been estimated and the conduction term measured by Roach. Precipitation at Kew during the year considered was about 15 per cent below the mean value, the deficit being concentrated in the winter months. This is not an unusually large deviation, and its effect on the overall energy balance is not large, as may be seen from Fig. 2 which includes all the known terms. The value of 0.5 mw. cm^{-2} used for the heat absorbed or emitted by the atmosphere in the three month periods is a rough estimate of a small term. It corresponds to an overall temperature change of 4°C in three months. The balances, to be accounted for by advective and dynamical heating, are

Year	-5 ± 3.5 mw. cm^{-2}
Three summer months	$+1.8 \pm 3.5$ mw. cm^{-2}
Three winter months	-11.8 ± 3.5 mw. cm^{-2}.

A non zero mean dynamical heating term implies a mean vertical velocity. The possible magnitude of the term may be estimated using some computations of Bannon (1948). The rainfall in the year considered was rather more than 500 mm., a mean rate of 0.055 $mm.hr^{-1}$. According to Bannon an atmosphere defined by the 60°F saturated adiabat requires a vertical velocity of about $+3 cm.sec^{-1}$ between 1000 mb. and 300mb. to produce a rainfall rate of 1 $mm.hr^{-1}$. The mean vertical velocity required to produce the observed rainfall is thus about 0.17 $cm.sec^{-1}$ and the rate of working, $\overline{\omega} \int \alpha dp$, about 12 $mw.cm^{-2}$, i.e. more than twice the rate of release of heat by condensation. This dynamical cooling would normally be approximately balanced by dynamical heating in the descending limbs of the vertical circulations producing the rainfall, but it is clear that the rates of working involved are so large that very small systematic vertical circulations or even random fluctuations about a zero mean vertical velocity might well dominate the energy balance of a single station over a period of a year or less. The vertical velocities involved are of course much too small for direct detection.

Some idea of the size of the advective term may be obtained from studies of heat transport such as those of Priestley (1949), White (1951) and Mintz (1954), some of whose results are shown in Fig. 3. Mintz computed $c_p \overline{\rho v_g' T'}$ for a series of pressure levels where v_g is the poleward component of geostrophic wind, T the temperature, and the primes denote deviations from mean values round a circle of latitude over the period concerned. White's figures are for $c_p \overline{\rho v' T'}$, v now being the observed poleward wind component. His study was restricted to N. American stations. Priestley computed $c_p \overline{\rho v' T'}$ for a single station, Larkhill, so that here the primes indicate deviations from a time mean and heat transport by horizontal standing eddies is not included. Raethjen's estimates of advective transport of heat plus potential energy for the winter and summer half years, derived from estimates of radiation balance, water balance, and storage of heat, are also shown in Fig. 3 which is in terms of the variation with latitude of the poleward energy flux F in mw. cm^{-1}.

/The

The local heating by the process producing F is given, in mw.cm^{-2} by the expression $-(\partial F/\partial\phi - F\tan\phi)/r$ (where ϕ is the latitude and r the radius of the earth); its magnitude at $\phi = 52°$ is approximately:-

Mintz	Two summer months	+1.0 mw. cm^{-2}
	Two winter months	+1.5 mw. cm^{-2}
Raethjen	Year	+0.5 mw. cm^{-2}
	Six summer months	-2.5 mw. cm^{-2}
	Six winter months	+3.5 mw. cm^{-2}.

The close general agreement between the estimates of Raethjen (flux of heat and potential energy), White (flux of heat) and Mintz (heat flux accounted for by geostrophic wind) poleward of 50° indicates that no appreciable mean vertical circulation is active in this region, so that there is no dynamic heating component in the latitude-mean heat balance. There is thus a less close agreement between the Kew regime of advective and dynamical heating and the latitude mean than was found for the radiation balance alone. Comparison with Raethjen's work in detail shows that the water phase change term and the storage term at Kew are much below the latitude average. The low value of the heat transport found by Priestley for southern England, in comparison with the figures of White and Mintz, suggests that horizontal standing eddies are of importance in this region, and non zero mean vertical motion might well be associated with such eddies. This is the type of question which might be elucidated by successful conclusion of the I.G.Y. programme.

6. CONCLUSIONS, WITH PARTICULAR REFERENCE TO THE I.G.Y. PROGRAMME

This study in combination with that of Roach suggests that the programme of radiation measurements proposed for the I.G.Y. can make a useful contribution to solution of the meteorological problem, i.e. that results of useful accuracy can be obtained with apparatus which is available, not unreasonably expensive, robust, and not too difficult to maintain. The minimum requirements are records of net radiative flux at the ground and solar radiation on a horizontal surface. Precipitation should be measured and an estimate of evaporation will be required which should be supported by all possible measurements (though it is hardly possible to recommend a method). A refinement which should be adopted at as many stations as possible is measurement of solar radiation in the infra-red, so that separate estimates of albedo in the infra-red and visible plus ultra-violet can be made. This allows comparison with estimates of the planetary albedo by the method of Danjon, which will almost certainly be confined to the visual and possibly near ultra-violet regions.

It has been shown that the inaccuracy to be expected in estimates of the local net radiation excess of the atmosphere - surface system is rather large in comparison with the seasonal means for the latitude belts. The major source of uncertainty is the value taken for the outward atmospheric radiation, and it is most likely to be reduced by many further measurements on the lines of those of J.T. Houghton combined with theoretical work on radiative transfer aimed at developing a sound substitute for the present radiation charts at high levels. It cannot be expected that this problem will be decisively resolved before or during the I.G.Y., but it will be possible to combine future results with I.G.Y. data. The uncertainty due to errors of the estimated albedo has been assessed as about half that of the long-wave radiation to space. It can be reduced by extensive measurements by Danjon's method. It is believed that an attempt will be made to encourage these during the I.G.Y., but the method is no doubt much simpler in principle than in practice, and the co-operation of astronomical observatories will be required. A more direct check of local estimates of albedo is provided by measurement of the downward and upward flux of solar radiation from aircraft to as high

/levels

levels as possible, comparing the results either individually with simultaneous estimates from ground measurements in the same locality, or in the mass with means such as those derived in this paper. Fritz (1948, 1950) has reported a few aircraft measurements in the U.S.A. and in this country the M.R.F. has begun systematic collection of data. It will be possible to apply the results of such investigations retrospectively to I.G.Y. data.

It also appears that the individual items of the local energy balance over a season or a year may differ very significantly from the long term mean, and this may well be true for a whole circle of latitude. It follows that to realise the full value of the I.G.Y. measurements a few selected stations should maintain the same routine for a period of say five years. This aspect is of course not confined to the radiation measurements. Continuous recording of solar radiation is now widespread and it should not be too difficult to add a record on the lines of that of Roach at a few stations.

In summary the conclusions are

(1) Radiation measurements recommended during the I.G.Y. can be made with a useful degree of accuracy, given care and frequent standardisation.

(2) The accuracy, and therefore the utility, can best be increased by measurements in the air of solar and atmospheric radiation. Such measurements wherever and whenever they are made deserve support as part of the I.G.Y. programme.

(3) The year to year variability of the various meteorological elements is an important factor. To determine this a few stations operating during the I.G.Y. should extend their measurements over a period of at least five years.

Appendix 1

The solar constant and scales of radiation

The value of the solar constant, and the spectral distribution of the extraterrestrial radiation are required before albedos can be estimated by the present method. The data used have been those suggested by Nicolet (1951a, 1951b). Johnson (1954) has recently published a new appreciation of the data on which the solar constant and the spectral distribution of solar energy are based. Nicolet's estimate for the solar constant was 138.0 mw. cm^{-2}, Johnson's 139.4 mw. cm^{-2}. Nicolet considered that his value might be in error by as much as ±5%, Johnson his by ±2%. This very satisfactory agreement does not extend to the details of the spectrum though both authors consider the relative accuracy of their data to be much higher than the absolute accuracy of their solar constant. The energy in certain ranges according to these authors is (in mw. cm^{-2})

Range	$\lambda < 0.3\mu$	$0.3\mu < \lambda < 0.4\mu$	$0.4\mu < \lambda < 0.7\mu$	$0.7\mu < \lambda < 3.0\mu$
Nicolet	0.96	8.2	57.7	70.8
Johnson	1.34	10.5	56.9	70.3

whilst the extraterrestrial illumination computed from their detailed spectra is

Nicolet 142.0 kilolux
Johnson 136.7 " .

Nicolet's relative values in the visual region depend mainly on astrophysical arguments connected with the solar emission, Johnson's on the extrapolation to zero air mass of measurements at the ground. The non specialist has little guidance when choosing between them, indeed he may well be surprised at the confidence expressed by each author in his chosen method. The difference in the extraterrestrial illumination arises mainly from differences in the spectral region $0.56\mu < \lambda < 0.62\mu$, which is very close to the long wave-length limit of the measurements on which Johnson relies. The difference in the extraterrestrial illuminations is large enough to be detected by careful and prolonged photometric measurements at the ground. The Kew record is certainly easier to fit to a value of 142 kl. than to 137 kl., indeed it has been inferred that the Kew measurements are systematically high because the albedo deduced from them assuming 142 kl. outside the atmosphere is low in comparison with that obtained by other methods. The discrepancy is greatly magnified if 137 kl. is used.

The probable errors of the estimated albedos given in the present paper include no allowance for the probable error of the solar constant. If Johnson's figures had been used rather than Nicolet's the derived total and visual plus ultra-violet albedos would have been about 1% higher and the photometric albedos about 4% lower. As far as energy balances are concerned the differences are of no importance in view of other uncertainties. In questions of photometry however, (for example in comparisons with Danjon's method) the difference is quite significant and it is important that it should be resolved.

A second source of systematic error is introduced in standardisation. Two instruments are in general use in meteorological services - the Ångström compensation pyrheliometer and the Smithsonian silver disc pyrheliometer. The Ångström instrument is used at Kew. It is not used absolutely, but is referred to a scale maintained in Sweden. Guild (1937) has shown that the scale as embodied in the Kew instrument in 1936 agreed within 0.5% with that maintained at the National Physical Laboratory. Guild (1937) and Eldridge (1952) have shown that the Ångström scale as embodied in the Kew instrument differs from the scale on which the Kew example of the Smithsonian instrument is calibrated ("Smithsonian scale of 1913") by 2.7%. The generally accepted difference between the Smithsonian 1913 and the Ångström scales is 3.5%, and

/it

it is almost certain that individual instruments, in use in various services as standards, differ from the mean of their type by at least 2%. There is a strong possibility of systematic differences of as much as 5% between the records of different meteorological services, even when these records are carefully maintained in reference to a local standard. Some effort is being made to reduce these differences in Europe and Africa. More extensive intercomparison of local standards could well form part of the I.G.Y. programme.

Table I

Mean values of total radiation and illumination

Period	At ground		Extraterrestrial	
	Radiation mw.cm^{-2}	Illumination kl.	Radiation mw.cm^{-2}	Illumination kl.
Year. May 1953-April 1954	10.4	13.8	27.9	29.0
Mean Year. 1947-1951	10.7	13.4		
May, June, July 1953	18.4	24.5	46.0	47.9
Mean. May, June, July 1947/51	19.1	24.2		
Nov., Dec. 1953 Jan. 1954	2.4	3.3	9.8	10.2
Mean. Nov., Dec., Jan. 1947/51	2.6	3.0		

Table II

Absorption and albedo of the cloudless atmosphere at Kew, expressed as a fraction of the extraterrestrial solar radiation in the range concerned (From MRP.894)

Period	Sin $\bar{h}$	O_3 Absorption		Water Absorption(I.R.)		Haze Absorption	Albedo			Total
		U.V.+Vis.	Illumination	2cm	1cm		$\lambda < 0.64\mu$	$\lambda > 0.64\mu$	Photometric	
Year	0.54	0.06	0.03	0.24	0.18	0.09	0.30	0.08	0.25	0.16
May, June, July	0.71	0.05	0.02^5	0.22	0.15	0.07	0.20	0.05	0.17	0.13
Nov., Dec., Jan.	0.23	0.08	0.07	0.28	0.24	0.15	-	0.11?	0.38	0.20

G.23465(c)/PN/8/55/50

Table III

Summary of assumed absorptions and derived albedos

Period	Case	Ultra violet + visual		Photometric		Infra-red		Total	
		Abs.	Alb.	Abs.	Alb.	Abs.	Alb.	Abs.	Alb.
May 53	a.1.	.10	.56	.08	.50	.30	.35	.20	.46
to	a.1.1.					.35	.30	.22^5	.43
Apr. 54	a.1.2.					.40	.25	.25	.41
inc.	a.2.	.15	.51	.12	.46	.35	.30	.25	.41
"	a.2.1.					.40	.25	.27^5	.38
"	a.2.2.					.45	.20	.30	.36
"	b.	.06	.60	.03	.52	.25	.40	.15	.50
"	b.1.					.30	.35	.17^5	.48
"	b.2.					.35	.30	.20	.45
May	c.1.	.10	.53	.07	.47	.30	.33	.20	.43
June	a.1.1.					.35	.28	.22^5	.41
July	a.1.2.					.40	.23	.25	.39
1953	a.2.	.15	.48	.12	.42	.35	.28	.25	.38
"	a.2.1.					.40	.23	.27^5	.35
"	a.2.2.					.45	.18	.30	.33
"	b.	.05	.58	.02	.49	.25	.38	.15	.48
"	b.1.					.30	.33	.17^5	.45
"	b.2.					.35	.28	.20	.43
Nov.	a.1.	.13	.66	.12	.60	.30	.48	.21^5	.57
Dec.	a.1.1.					.35	.43	.24	.55
1953	a.1.2.					.40	.38	.27	.52
Jan.	a.2.	.18	.61	.17	.55	.35	.43	.24	.52
1954	a.2.1.					.40	.38	.27	.49
"	a.2.2.					.45	.33	.29	.47
"	b.	.08	.71	.07	.61	.25	.53	.19	.62
"	b.1.					.30	.48	.21	.60
"	b.2.					.35	.43	.24	.57

Table IV

Probable values of the albedo of the mean atmosphere at Kew

Period	Vis + U.V.	Photometric	I.R.	Total
May 1953 - Apr. 1954	.56	.50	.33	.445
May, June, July 1953	.55	.48	.31	.43
Nov., Dec. 1953 Jan. 1954	.63	.57	.35	.495

Table V

Albedo of clouded part of atmosphere

Source of data	Vis + U.V.	Photometric	I.R.	Total
World (Fritz/Danjon case 1)	.63	.56	.39	.52
Kew mean	.67	.61	.44	.56
Kew persistent overcast	.79	.79	.51	.65

Table VI

Some terms in the energy budget of the surface at Kew (after Roach).
Unit mw.cm^{-2}, positive upwards

Period	Net Radiation flux			Heat flow to ground	Evaporation	Convection	Precipitation
	Total	Solar	Terrestrial				
May 1953 - Apr. 1954	-4.0±0.5	-7.8±0.2	+3.8±0.5	+0.05±0.1	+3.6(±0.5)	+0.5±1.0	4.0
May, June, July 1953	-8.8	-13.8	+4.9	-0.4	+6.8	+1.7	5.6
Nov., Dec. 1953 Jan. 1954	+0.7	-1.8	+2.5	+0.4	+0.7	-1.0	2.3

References

Bannon, J.K. 1948 The estimation of large scale vertical currents from the rate of rainfall. Q.J.R. Met. S., 74, pp.57-66.

Blackwell, M.J. 1954a Meteorological Research Papers, London. No.831.

1954b Meteorological Research Papers, London. No.895.

Blackwell, M.J., Eldridge R.H. and Robinson G.D. 1954 Meteorological Research Papers, London. No.894.

Drummond, A.J. and van Deventer, E.N. 1954 The atmospheric transmission of solar energy over Southern Africa. Notos, 3, pp. 272-284.

Eldridge, R.H. 1952 A comparison of substandard pyrheliometers. Q.J.R. Met. S., 78, pp. 260-264.

Fritz, S. 1948 The albedo of the ground and atmosphere. Bull. Amer. Met. Soc., 29, pp. 303-312.

" 1949 The albedo of the planet earth and of clouds. J. Met., 6, pp. 277-282.

" 1950 Measurements of the albedo of clouds. Bull. Amer. Met. Soc., 31, pp. 25-27.

Guild, J. 1937 Investigations in absolute radiometry. P.R.S., A161, pp. 1-38.

Houghton, H.G. 1954 On the annual heat balance of the northern hemisphere. J. Met., 11, pp. 1-9.

Houghton, J.T. 1954 Dissertation. Oxford.

Johnson, F.S. 1954 The solar constant. J. Met., 11, pp. 431-439.

Mintz, Y. 1954 The mean geostrophic poleward flux of angular momentum and sensible heat in the winter and summer of 1949. Univ. California, Los Angeles, Sci. Rep. No.7, Contract AF19(122)-48.

Nicolet, M. 1951a Sur la problème de la constante Solaire. Ann. Astrophys., 14, pp. 249-265.

1951b Sur la détermination du flux energetique du rayonnement extraterrestre du soleil. Arkiv. Met. Geophys. Bioklimat. 13. 3, pp. 209-219.

Priestley, C.H.B. 1949 Heat transport and zonal stress between latitudes. Q.J.R. Met. S., 75, pp. 28-40.

Raethjen, P. 1950 Kurzer Abriss der Meteorologie dynamisch gesehen II. Wärmeshaushalt der Atmosphäre. Hamburg. Published by the author.

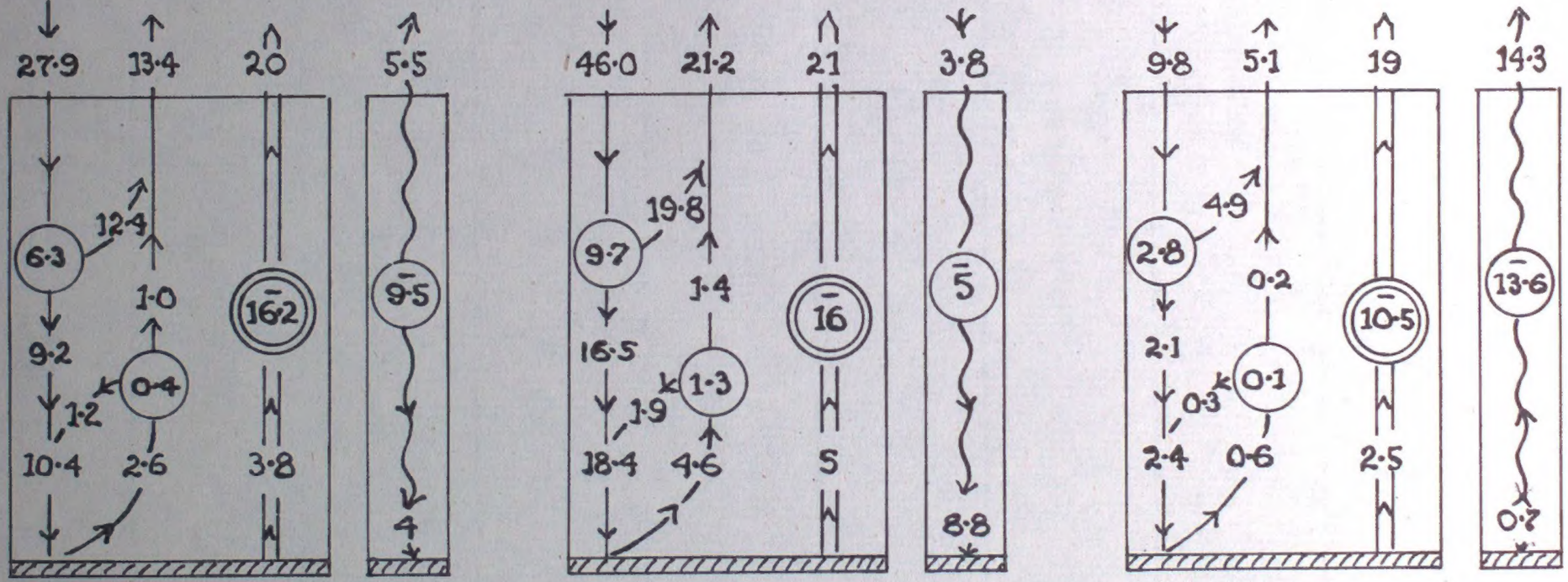
Roach, W.T. 1955 M.S. submitted to M.R.C.

/Robinson,

Robinson, G.D.	1947 1950	Notes on the measurement and estimation of atmospheric radiation, 1 & 2. Q.J.R. Met. S., 73, pp. 127-150 and 76, pp. 37-51.
Simpson, G.C.	1929	The distribution of terrestrial radiation. Mem. R.Met. S., 3, pp.53-78.
White, R.M.	1951	The meridional eddy flux of energy. Q.J.R. Met. S., 77, pp. 188-199.
Yamamoto, G. and Sasamori, T.	1954	Measurement of atmospheric radiation. Sci.Rep., Tohoku Univ. Geophys. Ser. 6, pp. 19-31.

M.R.P. 929

FIG. 1 RADIATION BUDGET OF SURFACE + ATMOSPHERE AT KEW.



1a YEAR

1b MAY. JUNE. JULY.

1c. NOV. DEC. JAN.

SOLAR RADN.

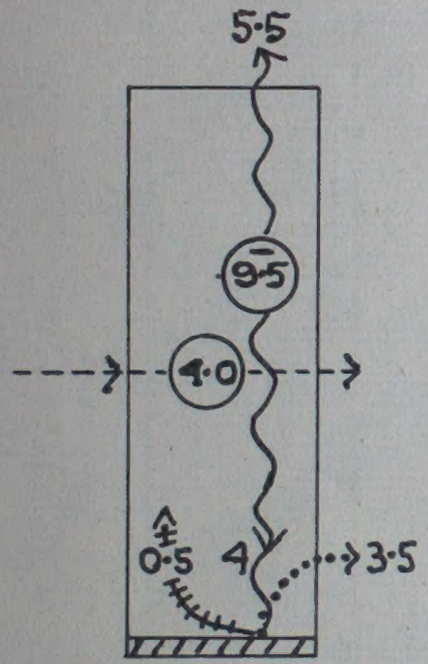
TERRESTRIAL RADN.

TOTAL RADN.

RADIATION IN MW.CM.$^{-2}$ ABSORPTION IN CIRCLES

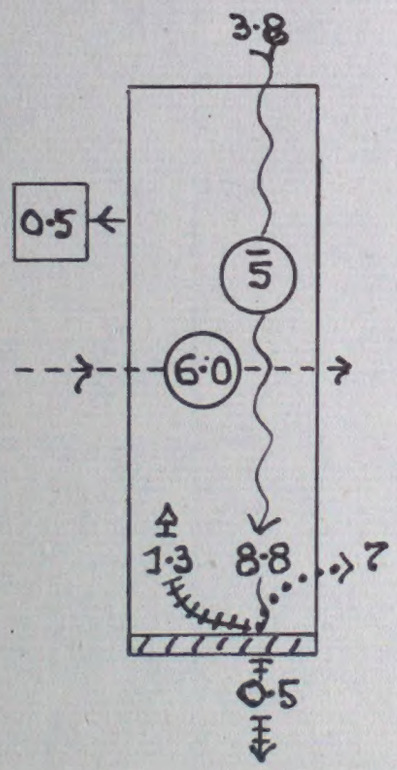
FIG 2. ENERGY BUDGET OF SURFACE + ATMOSPHERE. KEW. UNIT - MW.CM^{-2}.

2a. YEAR



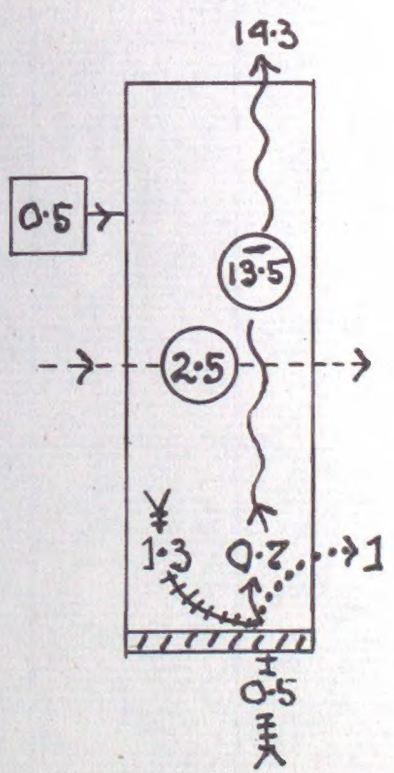
NET GAIN -5

2b. MAY, JUNE. JULY.



NET GAIN +1·8

2c. NOV. DEC. JAN.

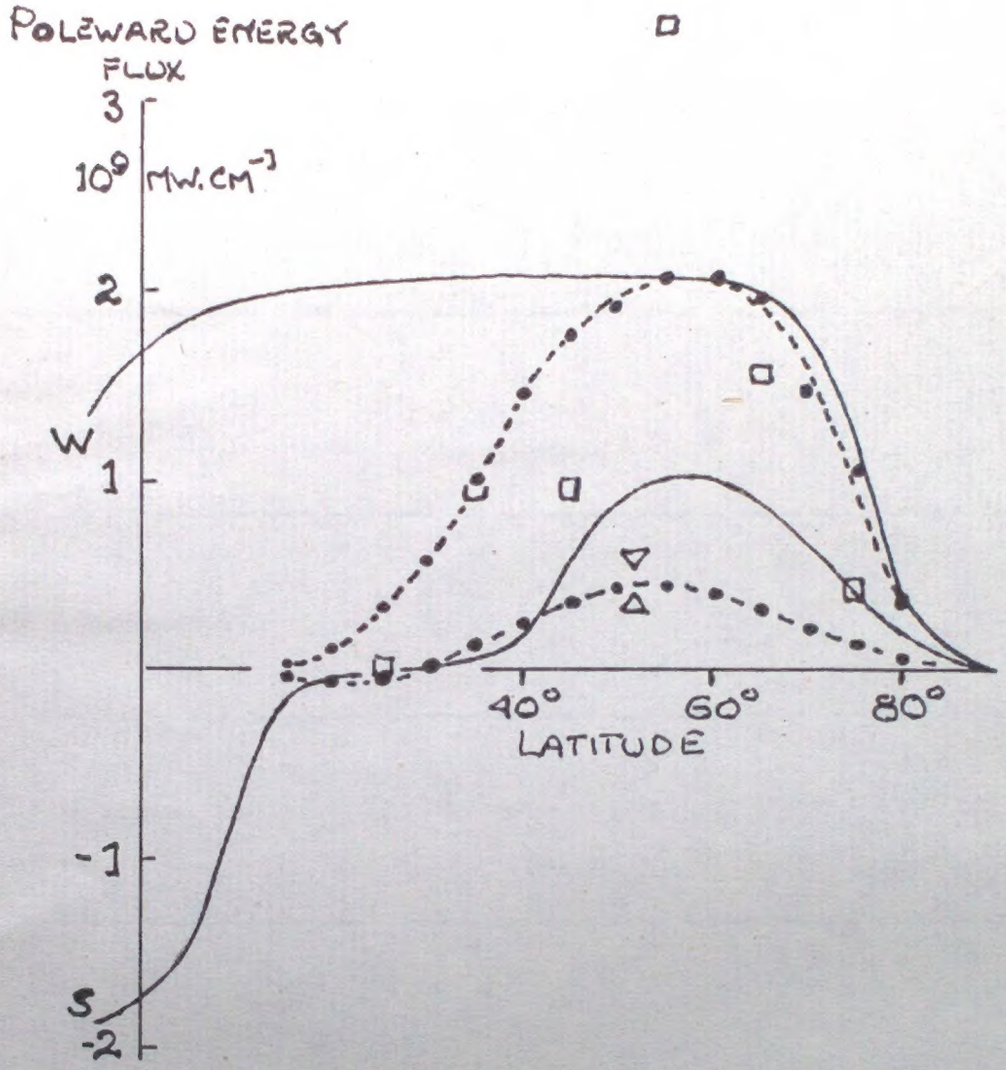


NET GAIN -11·8

TOTAL RAD^{N} — PRECIPITATION — EVAPORATION

CONDUCTION / CONVECTION TO AIR AND GROUND — AIR TEMPERATURE CHANGE

FIG 3. POLEWARD ENERGY FLUX DETERMINED BY VARIOUS METHODS.



W —— RAETHJEN. HEAT AND POTENTIAL ENERGY. WINTER.
S —— " " " " " SUMMER
- - • - - MINTZ. HEAT BY GEOSTROPHIC WIND N. HEMISPHERE. JAN./FEB. AND JULY/AUG. 1949
□ WHITE. HEAT BY OBSERVED WIND N. AMERICA FEB. 1949
△ PRIESTLEY. HEAT BY OBSERVED WIND LARKHILL MAY/JUNE/JULY/AUG. 1946/47.
▽ " NOV./DEC./JAN./FEB. 1946/47.

M.R.P. 929